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RESULTS OF A STUDY OF THE MALAKAL CHONDRITE (SUDAN)

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16. Abstract

The paper discusses the structure of the Malakal meteorite, which fell in the Sudan at the beginning of August 1970. The primary minerals proved to be olivine, orthopyroxene, nickel iron, and troilite. Chemical analysis was performed separately on the magnetic and nonmagnetic portions of the meteorite, and according to the resulting data, this meteorite belongs to the L group of chondrites. Mineralogically, it is shown to belong to the hypersthene olivine chondrites. The radiogenic ages of the meteorite were computed.

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RESULTS OF A STUDY OF THE MALAKAL CHONDRITE (SUDAN)

by

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A sample of stony meteorite, which has been named the Malakal meteorite, was sent to Moscow for analysis by S. M. el Rabaa, chairman of the Department of Geology of Khartoum University to A. M. Daminova, professor at the Patrice Lumumba People's Friendship University at the beginning of September, 1970. S. M. el Rabaa reported the following in letters of 31 August 1970 and 15 April 1971. /82***

The meteorite fell at the beginning of August 1970 at about 4 a.m. near the city of Malakal (approximate coordinates 9°30' N, 31° 31' E) in the province of Upper Nile in the Democratic Republic of the Sudan. The fall of the meteorite was accompanied by a loud din, which attracted the attention of the populace and which aroused army personnel located in this area. The meteorite was discovered about four hours after it fell. It was slightly elevated above the surface of the land, without any rock exposure. An odor issued from the meteorite, recalling the smell of gunpowder. The meteorite was delivered to the Department of Geology of Khartoum University by Captain Yahel el Zeiber on 11 August. The sample delivered, measuring 15 x 10 x 8 cm and weighing about 5 kg is part of an individual specimen whose initial dimensions and weight was unknown.

* Deceased.

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*** Numbers in the margin indicate pagination in the foreign text.

Data on the fall of the Malakal meteorite were reported somewhat later in the Meteoritnyy Byulletin (No. 50, 1971).

A lump of the Malakal meteorite weighing about 800 g was sent to Moscow. The portion of this lump remaining after our investigations, weighing about 500 g, is preserved in the collection of the Committee on Meteorites of the USSR Academy of Sciences (Sample No. 15034) in Moscow.

Exterior View and General Structure of the Meteorite

The sample obtained by us is a lump sawed off from an individual specimen. Its largest surface, of a polycylindrical shape, the natural surface of the meteorite, is covered with a black, tarnished fusion crust. The surface is smooth, but from one side has a regmaglyptal relief (photogram 1, 1a)* The regmaglypts have an elongated shape of up to 2 cm in length, 1 cm in width, and 0.5 cm in depth. /84
They are arranged in a subparallel fashion, which is usually observed on the lateral surfaces of a body that has passed through the terrestrial atmosphere. The remaining surfaces of the sample are the saw-cut planes and an artifical cleavage.

In a fresh fracture the meteorite is light gray, with a metallic glint from particles of nickel iron and troilite. The meteorite is very dense and hard. It has a chondritic texture[1], complicated by recrystallization and brecciation. Chondrules are plentiful. They are found in a dense mass made of silicates in which particles of nickel iron and troilite are sufficiently uniformly, sometimes annularly, distributed (photogram 1, 1b)*. Their diameter usually

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[1]The implication (Dawoud, Vail, 1971) that the Malakal meteorite is similar to the Kapoeta meteorite is in error, since the latter is an achondritic meteorite.

*Translator's Note: not reproduced here.

does not exceed 1 mm, though particles of elongated form reaching 2 mm and even individually 6 mm are sometimes encountered. A sub-parallel distribution of these particles is noted in places.

The characteristic feature of the meteorite is its brecciation and the presence in it of multiple stringers of up to 1 mm in thickness (photogram, 1, 1c, 2)*. The direction of some of them in places is parallel to the elongation of the nickel-iron particles. The stringers often intersect the chondrules and contain their fragments, and sometimes the entire chondrules. Some black stringers are joined to the fusion crust, and in these cases it can be seen that their nature is similar to that of the crust.

The Structure of the Meteorite and of its Chondrules

The chondritic texture is distinct under the microscope, though its general structure is extremely inhomogeneous. Chondrules amount to 80-85% of the total volume, the embedding mass taking up the remainder, which consists of almost equal quantities of silicates and opaque minerals.

The chondrules are usually spherical, ellipsoidal, more rarely polygonal in form, and deformed in places. Their diameter is usually 0.5-1.0 mm, more rarely 1.5-2.0 mm, often 3-4 mm. Chondrules are frequently broken up by fissures along which their particles are shifted;some chondrules are completely fragmented. Chondrules are encountered with sharp contours, though the clarity of the contours is more often lost: they are as if blurred as a consequence of their recrystallization and merge with their embedding mass. Chondrules are sometimes encountered in the form of regular globules and ellipsoids (photograms 1, 3)*. Chondrules in separate sections are arranged densely adjoining each other, so

*Translator's Note: not reproduced here.

that their shape is deformed, their contours indistinct, and they have a tendency toward a subparallel arrangement. Almost all known chondrule textures are observed: holocrystalline, eccentrically radiated, barred, and microporphyritic. The chondrules are often composed of elements of different texture, for example, barred and holocrystalline; combinations of other textures are also encountered. Monocrystalline olivine chondrules are rare, vitrified ones are not found; blended chondrules are encountered. Holocrystalline chondrules consist of rounded polygonal granules of olivine and opaque minerals. The quantity of the latter is variable. Sometimes they are up to 25% of the chondrule by volume, though these minerals are often lacking in the composition of the chondrule. The eccentric-radiated chondrules consist of fine prismatic crystals of orthopyroxene, occasionally relatively large, arranged in the form of rays from centers located on the periphery of the chondrule. Chondrules of complex texture are usually large and consist of olivine in more or less isometric, sometimes idiomorphic,grains and of orthopyroxene in the form of radially fibrous aggregates located between the olivine grains. Minute granules of opaque minerals are often found between the separate silicate grains. Bar-textured chondrules are composed of skeletal crystals of olivine and trace elemnts of plagioclase, or maskelynite and other minerals /85 (photogram 1; 4)*. We should note the barred chondrule with deformed 'bars' of olivine, fractured in the central part of the chondrule and welded with a plagioclase aggregate.

Chondrules of microporphyritic texture consist of minute isometric or idiomorphic grains of olivine, surrounded by a dark, weakly polarizing matrix which is a decrystallized glass with capillary inclusions of opaque minerals. Single chondrules are encountered whose central part is composed of a fine granular aggregate of olivine with a trace element of opaque minerals, and whose periphery is composed of larger, weakly polarizing grains of

*Translator's Note: not reproduced here.

plagioclase with part completely isotropic, evidently having reverted into maskelynite. Minute plagioclase and maskelynite grains of less than 0.1 mm, usually of intricate contours, are also encountered along with minute grains of olivine within the chondrules and between them. Phosphates are also encountered in the chondrules as a trace element.

The host mass of the chondrule consists either of an aggregate of granuloblastic textured minerals or of a translucent aggregate of fragmental minerals.

The granuloblastic textured aggregate is usually arranged in the form of fringes around the chondrule and has a centric texture. It is composed of silicates that form concretions, with opaque minerals, to which plagioclase or maskelynite, in places phosphates, is combined, usually serving as the core.

Minerals

The primary minerals, the components of the meteorite, are olivine, orthopyroxene, nickel iron, and troilite. Olivine predominates. Its grains have a cleavage and for the most part are divided by coarse fractures, often parallel to the cleavage planes; the grains are frequently broken into pieces. The olivine is colorless under a microscope in transmitted light, possesses parallel extinction, though is undulating in most grains. According to the refractive index, measured in a submerged liquid (measurement error here and below is $\pm$ 0.004), Ng = 1.720 $\pm$, Np = 1.684 $\pm$ and according to birefringence Ng-Np = 0.036, olivine contains 22-23 mole percent Fa[2].

Orthopyroxene is significantly inferior to olivine in quantity.

[2]According to the diagram in the book of U. A. Dir et al., 1, 1965.

It is also colorless under a microscope, possesses perfect prismatic cleavage, and is usually undulating. According to the index of refraction, Ng = 1.688 ±, Np = 1.676 ±, and, according to the birefringence obtained thereby, Ng-Np = 0.012, it contains 19-20 mole percent Fs[3]. According to the division of the orthopyroxenes proposed by G. I. Prior for meteorites, it may belong to the hypersthene.

Plagioclase is a typical trace element. The colorless mineral observed in chondrules forming small polygonal sections from the minute grans between the chondrules belong to it. Its grain is without twins. It possesses low refraction and birefringence. Its mean index of refraction Nm = 1.528 ±. According to these optical properties it belongs to albite. Sections of plagioclase in places are entirely isotropic, or individual grains are isotropic, apparently having reverted to maskelynite. The index of refraction of the isotropic sections, the maskelynite, N = 1.513-1.518.

Phosphate is rarely encountered, though in the form of large grains of up to 0.5 in length and up to 0.5 mm in width that are highly fractured. It is colorless under the microscope. Birefringence is extremely low. It is uniaxial and negative according to an indistinct interference figure. Its index of refraction No = 1.615-1.20. According to optical properties it must belong to merrillite, i.e., to calcic phosphate corresponding in composition /86 to terrestrial whitlockite (Fuchs, 1962). We are keeping the name 'merrillite' since this mineral was earlier determined to be whitlockite.

We should note too a high-birefringent mineral often observed in the form of narrow fringing in the olivine and orthopyroxene, which reveals an oblique extinction. As more exact investigations were not possible, we may assume that it is a monoclinic pyroxene.

The opaque minerals of the Malakal meteorite, which compose up to 10% of the volume, are native iron, phosphide, (rhabdite), troi-

[3] Ibid., 2, 1965.

lite, and chromite.

The native iron is nickel iron, mainly kamacite, more rarely taenite. Nickel iron is observed in the form of irregular particles with meandering contours (photogram 2; 3)*, with dimensions usually in fractions of a millimeter, and with sections in the form of regular globules of dimensions no more than hundredths of a millimeter (photogram 2; 4)*. The irregular particles, as well as the globular segregations, are composed of nickel iron and troilite in the form of finely interpenetrated trace elements.

The irregular particles of nickel iron, as is evident after microscopic pickling with 2% nital, are usually composed of an aggregate of minute grains of kamacite to which sections of taenite are frequently added. The presence and arrangement of the minute granules of rhabdite (fused form) along the borders of the kamacite grains is very typical, indicating secondary formation of the aggregate (photograms 2; 5)*. Sections having the shape of plessite octahedritic fractions which are composed of finer kamacite grains with a diameter of 5-6μ and which are flash pickled with nital, are observed in the middle of the fine-granulated kamacite aggregate (photogram 2; 5)*. Sections of taenite are in places separated from the kamacite by a rim made of micro-textured kamacite and taenite. Separate particles, apparently of plessite of the same texture, are also observed. One particle with a cross-shaped arrangement of a kamacite beam (photogram 2; 6) is encountered. In general, the texture of nickel-iron particles is a recrystallization structure, very similar to the recrystallization structure of the octahedrites.

Many particles having the shape of nickel iron are composed either partially or entirely of troilite. Troilite forms an aggregate of fine granules or flakes. In reflected light under a microscope it is dirty yellowish in color, is pliochroistic, and anisotropic. It is not pickled with nital, but instantaneously

*Translator's Note: not reproduced here.

reacts to the effect of a hydrochloride acid solution, turbulently precipitating hydrogen sulphide. The particles such as globules that are encountered locally have the same composition. Their texture there where the troilite is blended with the nickel iron, is reminiscent of a micrographic texture.

Troilite and nickel iron also compose very fine stringers, intersecting the silicates and chromite or surrounding the spheroidal, as if fused, fragments of other minerals. The vitrified black opaque substance, like the substance of the fusion crust, in places forms a small zone made of a network of fine stringers.

Chromite is distributed quite uniformly. It forms isometric, subidiomorphic grains with a cross section of tenths of a millimeter that are highly fractured as a rule. The fissures in them are sometimes filled with troilite or nickel iron.

Two zones are distinct in the fusion crust of the Malakal meteorite. The outer crust is vitrified and black with a thickness of from 0.018 to 0.18 mm and made of opaque, highly porous glass. It is separated by a sharp, though very irregular boundary from the less porous zone of thickness 0.18-0.5 mm that gradually changes into the invariant substance of the meteorite. It is composed of semi-fused silicates, partially reverted into glass, permeated with very fine stringers and drop-like granules of troilite and nickel iron. This zone is fissured.

The investigations that were conducted demonstrated the follow- /87
ing typical features of the Malakal meteorite: high compaction for the total brecciation and abundant stringers; fracturing, fragmentation, and undulating extinction of the grains of the minerals, maskelynitized plagioclase, a structure of recrystallization of the nickel-iron and troilite particles and the presence of the latter

minerals in the shape of globular segregations and networks of stringers.

These features, which can be explained by the effects of shock waves, were described for a number of other chondrites belonging to the shock-metamorphized class (Anders, 1961; Heymann, 1967, Baldanza, Levi-Donati, 1971) and were earlier observed by one of the authors (L. G. Kvasha) in the Kunashak, Pervomay Village, and other group L chondrites.

Chemical Composition

The chemical compositon of the Malakal meteorite was determined from a small lump with weight of 14.3 g which sufficiently characterized the meteorite. Chemical analysis was conducted by methods that have been used by the Committee on Meteorites of the USSR Academy of Sciences (D'yakonova, Kharitonova, 1966). While preparing the sample for analysis we noticed its high density and hardness: it crumbled with difficulty in both a metallic and in an agate mortar. Magnetic and nonmagnetic fractions after curing at 100° C amounted to (here and below in wt.-%) 21.04 and 78.96, respectively. After treatment of these fractions with acid the soluble and nonsoluble portions of the meteoritic substance amounted to 42.35 and 57.65, respectively.

Under analysis it was noted that troilite is mainly concentrated in the magnetic fraction: sulphur in the magnetic fraction amounts to 5.11, and in the nonmagnetic fraction it amounts to 1.66. A high phosphorous enrichment of the magnetic fraction is also observed: P_2O_5 content in the magnetic fraction is equal to 1.24, and in the nonmagnetic fraction it is equal to 0.026. The assumption that the enrichment of the magnetic fraction with sulphur is caused by concretions of troilite with metal is entirely confirmed by microscopic investigation. Enrichment of the same fraction with phosphor is also explained microscopically.

A somewhat increased content of alkali metals in the Malakal meteorite, in comparison with their content in chondrites of the same chemical group, was noted. The Malakal meteorite, according to data from the chemical analysis,belongs to the L group of chondrites (Urey, Craig, 1953).

Oxides and elements	Wt.-%	Oxides and elements	Wt.-%	Elements	Wt.-%	Elements	Wt.-%
SiO_2	38,95	H_2O^+	0,31	Si	18,20	K	0,12
TiO_2	0,102	H_2O^-	0,04	Ti	0,061	P	0,122
Al_2O_3	2,72	Fe_{sulph}	4,16	Al	1,44	S	2,38
Cr_2O_3	0,50	S	2,38	Cr	0,34	Fe	22,24
FeO	12,90	(FeS	6,54)	Mg	14,97	Ni	1,24
MnO	0,34	Fe_{Met}	8,06	Mn	0,26	Co	0,074
MgO	24,85	Ni	1,24	Ca	1,50	Cu	0,0094
CaO	2,10	Co	0,074	Na	0,98	H	0,038
Na_2O	1,32	Cu	0,0094				
K_2O	0,144	(Metal	9,38)				
P_2O_5	0,28						
		Total	100,48				

[Translator's Note: commas represent decimals.]

Remarks:

Numbers in parentheses do not enter into the calculation of the total.

Fe_{tot} is 22.21; FeO/(FeO + MgO) = 22; Ni in metal is 13.22%; Co in metal is 9.79%.

The density of the meteorite determined by a suspension in CCl_4 is equal to 3.50 g/cm^3.

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The contents of stable isotopes of inert gases in the Malakal meteorite were measured on the MS-10 mass spectrometer under static conditions (table). The absolute contents of the isotopes were determined by the peak method. The cosmogenic Ar^{38}_{K} was calculated from the ratios $Ar^{38}_{K}/Ar^{36}_{K} = 1.6$ and $Ar^{38}_{(cult + primary)}/Ar^{36}_{(cult + primary)} = 0.187$ (Levskiy et al., 1971); its content turned out to be equal to $0.15 \cdot 10^{-8}$ cm^3/g. /88

Content and Isotopic Ratio of Inert Gases in the Meteorite*

He^4	Ne^{22}	Ar^{36}	Ar^{38}	Ar^{40}	He^4/He^3	Ne^{20}/Ne^{22}	Ne^{21}/Ne^{22}	Ar^{40}/Ar^{36}	Ar^{38}/Ar^{36}
54	1,4	0,5	0,25	315	11,8± ±0,2	0,52± ±0,02	0,84± ±0,01	620± ±8	0,468± ±0,007

Remark. The gas content in 10^{-1} cm^3/g under normal conditions. The error of an individual determination was 15%.

*Translator's Note: commas represent decimals.

The radioisotope Ar^{39} was also measured in the Malakal meteorite. Extraction and refinement of Ar^{39} were conducted on a special vacuum-pumping assembly. The activity of Ar^{39} was computed on a low-background radiometric instrument. The geiger counter used (Fisenko, Kolesnikov, 1971) had a background of (0.062 ± 0.002) imp/min and a detection efficiency of 90%. The measured activity of Ar^{39} is equal to (7.1 ± 0.2) dis/min·kg.

We present the values of the radiation age of the Malakal meteorite determined by different methods:

Method	10^6 years	Method	10^6 years
$Ar^{39} - Ar^{38}$	4.4 ± 0.7	Ne^{21}	4.3 ± 0.5
Ar^{38}	2.9 ± 0.5	He^3	2.4 ± 0.3

The errors derived include only the errors in measuring the isotopes. The cross-sectional ratio (σ) of the isotopes, $\sigma_{Ar^{39}}/\sigma_{Ar^{38}}$ was taken equal to 0.4 (Goebel et al., 1964). The rate of formation of Ne^{21} was taken equal to $0.28 \cdot 10^{-8}$ $cm^3/g \cdot 10^6$ yrs. This value corresponds to the ratio of Ne^{22}/Ne^{21} for this meteorite (Eberhardt et al., 1966). The rates of formation for He^3 and Ar^{38} were taken equal to $1.96 \cdot 10^{-8}$ and $0.0517 \cdot 10^{-8}$ $cm^3/g \cdot 10^6$ yrs., respectively.

We may consider the most probable value of the radioactive age of the Malakal meteorite to be $4 \pm 0.5 \cdot 10^6$ yrs.

The radiogenic age of the meteorite determined by the K-Ar method is equal to $570 \cdot 10^6$ yrs. Such a low age attests to the loss of radiogenic gases (Anders, 1964).

Conclusions

The Malakal stony meteorite is a crystalline, shock metamorphized chondrite.

Chemically it belongs to the L group of chondrites, and mineralogically it may belong to the hypersthenic olivine chondrites.

According to structural features it belongs to those meteorites that have been tested for shock metamorphism which caused strain, maskelytinization, partial recrystallization, and local fusion.

The low radiogenic age of the meteorite determined by the K-Ar method, which attests to the loss of radiogenic gases that could have occurred during flash heating, is also explained by shock metamorphism.

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